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SYNOPSIS An operating automated system has been developed for Wappapello Dam. The system allows periodic reading of foundation pore pressure sensors. Upon sensing strong ground shaking, the system reads rock and foundation triaxial acceleration. The acceleration readings cause the system to collect pore pressure rise in a loose, saturated sand. The data is available over telephone lines in real time. In addition to reducing maintenance piezometer reading labor, the automation performs earthquake triggering notification and remote data evaluation. The engineering use for dam safety review is considered invaluable.

INTRODUCTION

Earthquakes have long been a severe threat to structures in the New Madrid region of the central United States. Wappapello Dam was designed with consideration of the earthquake risk. The Wappapello project was designed and built, and is owned, by the U.S. Army, Corps of Engineers.

The recent seismic evaluation of the structure revealed a susceptibility of a loose, modern sand deposit to liquefaction. Since Wappapello's embankment and foundation are well studied and the structure is near the seismic activity produced by the New Madrid Fault, the opportunity to apply the electronic and computer technology to automating a monitoring system is beneficial.

The chief goals of this system are: to use seismic events to trigger piezometer data acquisition in the loose sand relating pore pressure to the measured shaking of that medium; and, to acquire, reduce, and transmit digital seismic data remotely. This will provide the district with prompt notification of an event and provide sufficient understandable information that can be related directly to dam performance. Previously, piezometers and seismic instruments could not be read remotely and seismic data required photographic processing prior to use.

This system is capable of providing statistical and graphical representations (documentation) of foundation and embankment reactions compared with accelerations, time, and hydraulic head fluctuations. This information will in turn be related to historical dam performance and continuing long-term analysis. This system is not intended to address location of an earthquake's epicenter or magnitude determination.

SITE INFORMATION

Wappapello Dam is located on the St. Francis River (Mile 309) in Sections 2 and 3, Township 26 north, Range 7 east, in the Ozark Uplands just north of the Mississippi Embankment of Wayne County, Missouri. It is 16 miles northeast of Poplar Bluff, Missouri, and 1 mile southwest of Wappapello, Missouri.

The dam was designed in the 1930s and completed in the early 1940s. The embankment of rolled earthen fill impounds the St. Francis River. The structure has a defensive embankment design in recognition of the region's earthquake threat. The dam is supplemented by an outlet conduit through the right abutment for controlling normal discharges from the reservoir and an uncontrolled concrete spillway, located beyond the outlet works in right abutment. The conservation pool for the lake is elevation (El.) 109.65 meters (m) to serve the needs of recreation and wildlife. The dam is a rolled earth structure with a crest length of 825 m. The crest, at El. 127.95 m has a crown-width of 9.1 m and a maximum height of 33 m above the original stream bed. The slopes of the dam are protected by rip-rap and a toe drain was installed a the downstream toe.

Seismic Environment

The dam is located within the Ozark Plateau Physiographic Province just a short distance from the Ozark Escarpment, the boundary with the Mississippi Embayment Province. The relief at the site is approximately 90 m. The faults in the vicinity of the site are not capable of producing earthquakes. The nearest seismic zone containing a discrete active fault is the New Madrid Seismic Zone, 50 kilometers (30 miles) to the southwest.

Wappapello Dam lies within the Ozark Random Seismic Zone near the West Embayment Seismic Zone. Locations of earthquakes for these two zones implies that a body-wave magnitude (mb)

6.1 earthquake could occur near the site. The governing large event for this location is an mb 7.5 earthquake within the New Madrid Seismic Zone, only 50 kilometers away. On a probabilistic basis, an event could produce a horizontal acceleration of 30 percent of gravity and a Modified Mercalli Site Intensity of IX for a mean annual return period of 1,000 years.

Engineering Design

The engineering was developed as follows:

> ...all concrete structures have been designed using a seismic force of 0.1g, i.e., 10 percent of the weight of the structure and equipment applied as a horizontal force, in any direction, acting on the center of gravity above the plane being considered. The earth dam is subject to these same seismic forces; however, due to the conservative side slopes proposed and the liberal factor of safety, it is believed that it will be of sufficient structural strength to resist any seismic forces that may be expected (USACE, Engineer Office, 1938).

Conservative embankment slopes (1V:8H bottom slope) and freeboard height (usually 18 m) are the chief defensive features for earthquakes. Loose, near-river sands were not recognized as a foundation impediment, although the site was investigated well. These Point-Bar sands were neither removed nor densified during foundation preparation for the embankment. The founding materials appeared adequate by the designers. Loose, saturated sands were not recognized as a seismic hazard prior to the Nigata Earthquake's damage.

Ordovician dolomites form the bedrock and left abutment of the site. A stiff, clayey, over-consolidated residual soil composes the right abutment of the embankment. The embankment is founded on deep alluvial fill (40 m in depth). Deeper soil strata are medium to dense sands and gravels interbedded with medium stiff overbank deposits. The Young Point-Bar deposit, placed recently by the St. Francis River, is a very loose to medium dense sand unit. As a typical Point Bar, the modern soil is an aggregate of layers that grade from coarse to finer overlying material. Overall, the Young Point Bar is a loose, saturated sand that may vary in composition and strength by location.

Liquefaction Potential and Embankment Stability

The Corps of Engineers has recognized the liquefaction potential and community risk. Three modern investigations have been conducted by the Corps. Memphis District and Waterways Experiment Station (WES) developed modern exploration, geophysical investigation and laboratory analyses. St. Louis District completed a probabilistic evaluation of the project (USAED-St. Louis, 1988, and Wolff, et al, 1988). WES with Dr. W.D. Liam Finn is presently completing a deformation assessment of the Wappapello embankment during seismic loading (Hempen, et al, 1992).

The Young Point-Bar deposit is the founding material of the Wappapello Dam embankment for one third of the dam's 670 m length. The Young Point Bar has been determined liquefiable by Seed's Simplified Procedure and dynamic, cyclic triaxial testing (USAED-St. Louis, 1988). Significant deformation of the embankment occurs with strong earthquake vibration (USAED-St. Louis, 1988, and Hempen, et al, 1992).

Piezometric System

The piezometric system was designed to monitor pore pressure in the Young Point-Bar sand during an earthquake event. Two piezometers (transducers) each were installed at approximately the same elevation and station at the crest, mid-slope and toe within the embankment foundation. The selection of the piezometers were dictated by their frequency response rate as well as reliability, sensitivity, and durability. To achieve the abnormally high sampling rate, semi-conductor strain gage transducers were selected over other types (vibrating wire or pneumatic). Transducers from three different manufactures were selected for future performance comparison and redundancy. Each set of transducers were installed in cased boreholes into the Point-Bar sand stratum. For the installation, each borehole was advanced below the open-ended casing to its elevation. The transducers were then lowered into place and back filled with sand of similar gradation properties of the existing medium. The backfill sand was brought well into the casing and the casing was then sealed with 1 m of bentonite. All transducer cables were installed in buried PVC conduit and routed to Remote Monitoring Unit (RMU) #1 located at mid-slope. In addition to the RMU-1 location, two other RMU locations (RMU-2 and RMU-3) were selected and integrated into the automated system for dam safety monitoring and analysis. A total of twelve transducers were installed (retrofitted) in existing open system piezometers and connected to RMU-2 and RMU-3. The transducers were installed in 1.27 cm (1/2 inch) PVC riser pipes at predetermined elevations and cabled to the RMU locations.

Strong-Motion System

A system of three downhole seismometers evaluate strong ground shaking at the site. Below the dam's centerline and near the downstream toe, downhole accelerometers have been placed within the Young Point Bar. The downhole packages have been placed at the same elevation and within a few meters horizontally of the Point-Bar piezometers. At the mid-slope location the accelerometer was installed in the Ordovician Gasconade bedrock.

All three downhole packages are Kinemetrics three-component, force balance accelerometers, FBA-13DH. The downhole units are linked by vulcanized cable to Kinemetrics Model SSA-1, digital accelerographs (Kinemetrics, 1989). The accelerographs are ganged together such that any 0.01 gravity (g) motion of one detector will initiate the other two units. (Two, surficial, film-based accelerometers will likely be integrated into the WS-ADAS for joint initiation.) The systems have a natural frequency of 50 hertz and 50% of critical damping. Full-scale reading is 1.0 g.

Closed-end, Schedule-80 PVC (nominally 0.10 m inner diameter) was used to stabilize the boreholes, due to the large overburden depths through saturated loose to dense soils. A soil-matching, bentonitic gel grout was backfilled about the casing annulus. The downhole packages have been locked into the bottom casing position by three methods for various reasons. The toe embankment accelerometer within the Point Bar uses a wedging system designed for accelerometer emplacements (Kinemetrics, 1988). The Point Bar accelerometer beneath the dam crest is encased with neat cement grout. The bedrock accelerometer is lock into position 50 m below the mid-slope with uniform, coarse, angular river sand.

WS-ADAS CONFIGURATION

The automation system was planned by the St. Louis District and co-designed/installed with Woodward-Clyde Consultants. The system installation was completed during the summer of 1991.

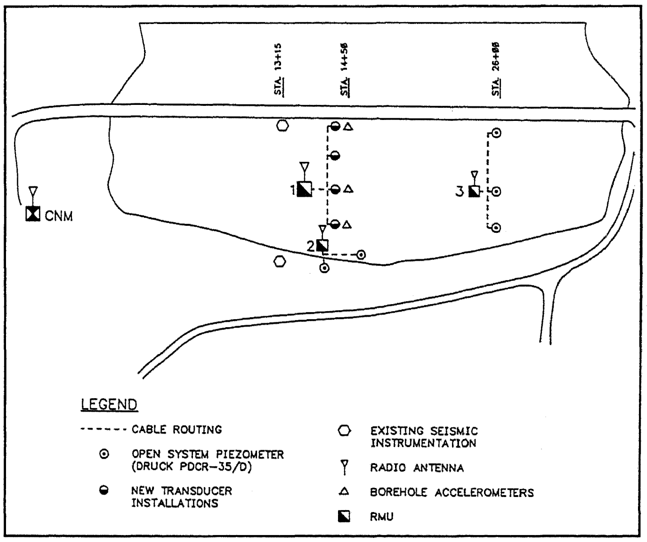

Figure 1 - Site Plan

The automation system design consists of three major components: the Central Network Monitor (CNM), RMUs, and the monitored Instruments. One of the major considerations during the system design phase was to limit customization where appropriate. Customization typically means proprietary hardware or software and inevitably higher maintenance costs. The system consists entirely of commercially available off-the-shelf components integrated into a single operating system.

The CNM is located in the project administration building approximately one Kilometer from the dam. A plan view of the overall site showing major component locations is presented in **Figure 1.** The CNM continuously monitors incoming UHF radio messages from RMU-1, requests data from RMU 2 and 3 via UHF radio, performs automatic telephone dial-out voice notification and provides the user interface either locally (at the project administration building) or via password secured remote telephone dial-in. **Figure 2** presents the overall system architecture.

RMU 1 is tasked with monitoring the three digital strong motion accelerographs and up to eight pore pressure instruments. RMU 2 monitors eight pore pressure instruments. RMU 3 monitors four pore pressure instruments. The system has two main modes of operation: normal mode, and event mode. In Normal Mode (**Figure 3**) the system acquires routine pore pressure readings on a user determined basis, typically daily.

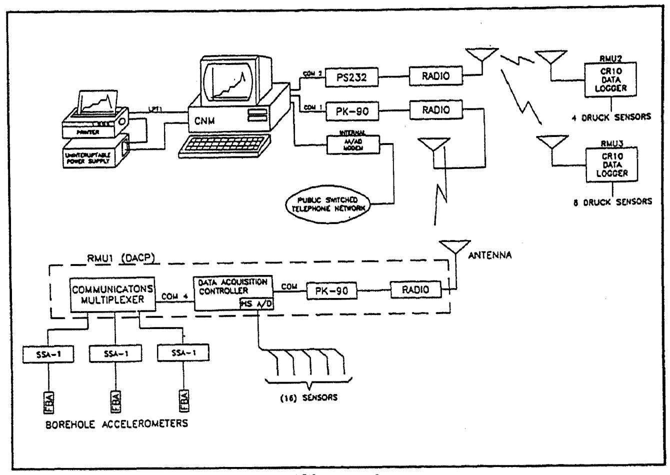

Figure 2
System Architecture

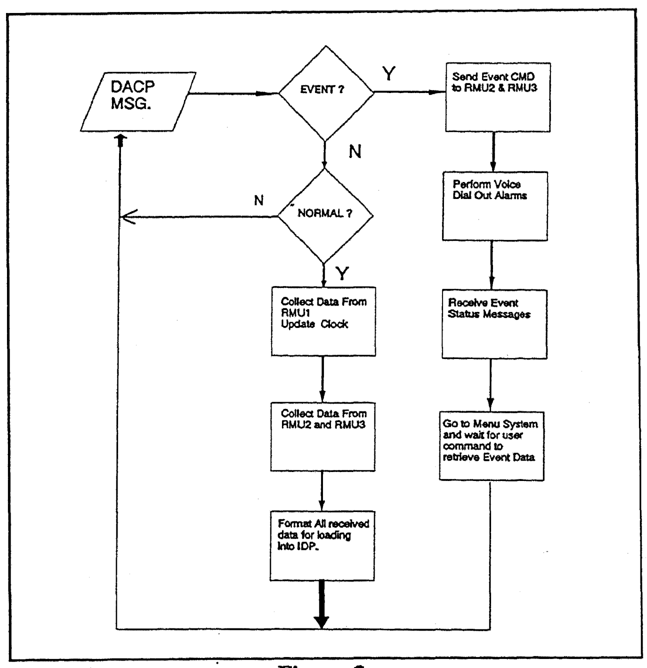

Figure 3
Main Software Flow Diagram

In Event Mode (**Figure 3**) the system acquires data at a much higher frequency as previously determined. Other event mode activities include the dial-out voice notification, and status message logging. Overall features of the system include lightening protection, alternative power supplies, alarms, and system integrity diagnosis as appropriate.

Central Network Monitor
The CNM is a PC-based system designed to store acquired data on a hard disk, reduce and plot data and transmit data to the District Office upon request. The system can be accessed by a remote user in the St. Louis District office, from the Wappapello Administration Building, or by any other authorized off-site user. The main function of the CNM is to provide an interface between human users and the various components of the system.

The CNM acts just as its name implies, it monitors the network. All automatic functions of the system are controlled by RMU 1. The manual operation of the CNM allows users to manually poll, (DEMAND) an RMU to take a reading and send back the results immediately. Any of the RMUs or the SSA 1 accelerographs can be accessed directly by using the TERMINAL function of the CNM. TERMINAL mode allows a user to connect directly to the device for the purpose of checking statuses or running diagnostic checks.

CNM Configuration
The CNM hardware configuration consists of a 386/25 MHZ PC/AT with 8 M-bytes of Random Access Memory (RAM), 120 M-byte hard drive, 5.25 inch and 3.5 inch diskette drives, one internal 2400 Bits Per Second (bps) modem, one internal voice massaging card, color VGA monitor, mouse. The CNM is equipped with an uninterruptible power supply (UPS) capable of running the CNM for approximately four hours in the event that there is a power failure.

A wide carriage printer is used to print reports and or alarm messages. The CNM is equipped with two radio sub-systems. One is comprised of a packet switched radio modem and UHF radio and is used to communicate with RMU 1. The other is a radio base station supplied by Campbell Scientific, Inc, of Logan, Utah and is used to communicate with RMU-2 and RMU-3. All of the CNM components are housed in a 19" standing electronic cabinet for maximum space efficiency.

Remote Monitoring Units
A UHF radio network of three remote monitoring units control data acquisition and intermediate data storage from the seismic and piezometric instrumentation.
RMUs communicate via radio to the CNM. Each of the RMUs are installed in environmentally secure enclosures on concrete pads on the embankment. All RMU locations are grounded to a grounding rod placed within the RMU enclosure or under the concrete pad. Lightning protection is provided for all sensors, sensor interfaces, and radio equipment. Each RMU has the capability to be preprogrammed to poll the sensors at predetermined time intervals and store the data until the data can be transferred to the CNM. Each RMU also has the capability of being calibrated, programmed, interrogated, and diagnosed via portable lap-top computer, the CNM, or from St. Louis.

RMU number 1 consists of the Data Acquisition and Communications Co-processor (DACP). The DACP contains the intelligence to continuously monitor three Kinemetrics SSA-1 digital accelerographs with borehole accelerometers for seismic event triggering. The DACP also contains a high speed highly accurate data acquisition system for making high speed pore pressure measurements of up to eight foundation piezometers installed at the location of the potentially-liquefiable Point-Bar sands (STA 14+50). The DACP is programmed to automatically vary the sampling rate when triggered by a seismic event (**Table 1**).

TABLE 1

Time Duration	Sample Type	Sample Rate
Event Duration	Seismic	100/sec./chan.
0 to 45 sec.	Piezometer	25/sec./instr.
45 sec. to 5 min.	Piezometer	10/sec./instr.
5 min. to 6 hours	Piezometer	1/min./instr.
6 hours to 42 hours	Piezometer	1/hour/instr.

In addition, RMU-1 triggers RMU-2 and RMU-3 via the CNM to start acquiring data at a preprogrammed rate of 1 sample/sec/channel for a duration of 10 minutes. In the event of an after-shock, the system will re-initialize and commence acquiring data at the higher frequency. Seismic data are stored at each Kinemetrics unit. All piezometer data are stored in a separate high speed data recorder. At the end of the seismic event the data are sequentially transferred to the DACP for later retrieval by the CNM. Piezometer data are acquired four times per day under normal operating conditions. All status and event messages are initiated by the DACP and acted on by the CNM. **Figure 4** shows the DACP block diagram.

RMU-2 is located near the dam toe at station 14+00 and RMU-3 is located at mid-slope at station 26+00. These two RMUs acquire pore pressure data from 12 retrofitted open tube piezometers currently monitoring foundation strata (other than Point Bar) and dam performance. These data are included in the evaluation of the structure as affected by seismic activity. The data collection and telemetry equipment are comprised of off-the-shelf solar powered units equipped with appropriate sensor and telemetry interfaces. The solar powered units reduce raw data to engineering units. **Figure 5** shows the Functional block diagram typical of RMU-2 and RMU-3.

SOFTWARE

The software installed at the CNM are comprised of two packages: The Network Control package which controls data acquisition, remote and

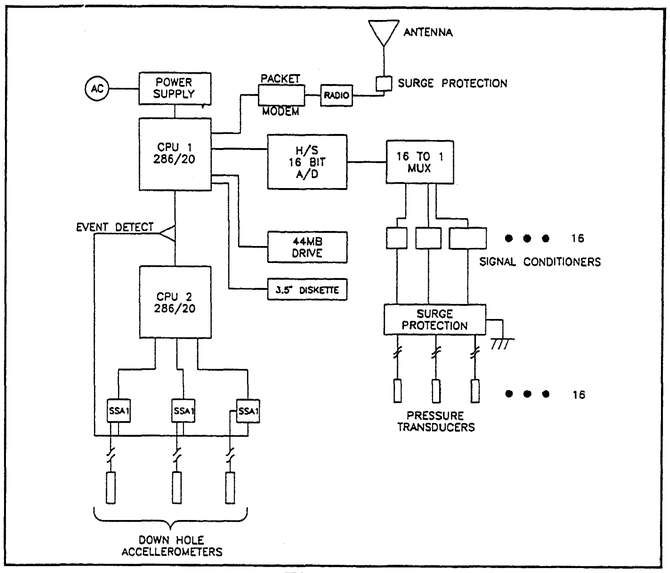

Figure 4
DACP Block Diagram

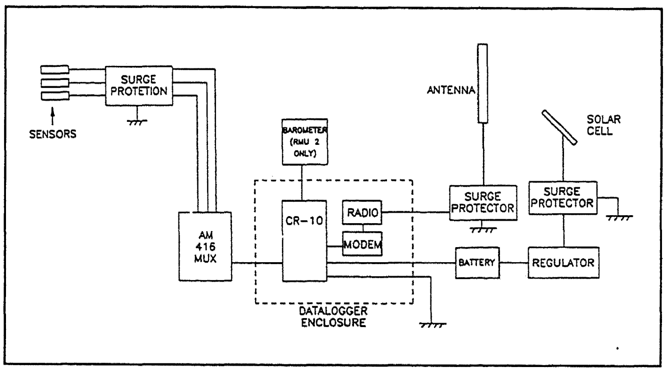

Figure 5
RMU 2/3 Block Diagram

site communications and alarms; and the Analytical package, which is utilized for all data reduction, analysis and plotting at the project site.

The software is menu-driven witch prompts the user to select required operations and supports user ID and password verification for local and remote users. The software is of modular design with programs and data sets maintained as separate entities. The CNM automatically starts upon reboot of the computer.

The Network Control Package controls data collection sequencing, network communications and performs system integrity checks. The program allows the local or remote users to reprogram variables. The software creates data file subdirectories to manage the large number of data files. The data are stored by instrument and event as well as by date and time of collection. Data can be acquired from individual instruments or groups of instruments upon command. The software will display information pertaining to the processing of event data at the seismic unit allowing the user to see the last event that occurred with the date, time, and the file name in which the data was placed.

The Network Control and Analytical Package is an accumulation of off-the-shelf software integrated into a multi-tasking environment. The multi-tasking environment is provided by a windows-like program called DESQ-VIEW (Quarterdeck Office Systems, 1991).

The database management software is a complete relational database product for the PC that is well supported and established within the industry. The database is configured to store the geotechnical data with time stamps as well as handle the large amount of data associated with the large amount of data associated with the seismic events. The system is menu-driven and utilize fill-in-the-blank user interfaces.

The Graphics software program processes the data and generates graphs on the screen and printer. Multiple graphics output are available to the user in a menu-driven interactive routine.

The Kinemetrics SWS-1 analysis and support software package is used for the analysis and plotting of the seismic data. The Kinemetrics software stores data in MS-DOS files in a format that is compatible with other data management uses.

The CNM is remotely accessed using an off-the-shelf remote control communications program called PC-ANYWHERE (Dynamic Microprocessor Associates Inc., 1990). PC-ANYWHERE provides total system security via multi-level password protection and supports the execution of any part of the CNM software capabilities including graphics and file transfers.The interactive terminal mode of the CNM software allows remote users to access the Kinemetrics SSA-1 accelerograghs directly. Diagnostics and parameter configuration is fully supported.

CONCLUSIONS

The WS-ADAS is a functioning, on-line system. It reads standard periodic, pore pressures in foundations and awaits earthquake initiation. The system aids earthquake damage warning and research objectives. While local staff may have "felt" the earthquake and proceeded to examine important dam features, engineering personnel will be alerted to the earthquake. The system may be fast enough for notification to proceed before telephone and power outages occur from larger earthquakes. Distant engineers with telephone availability and computer access may review pore-pressure rise and strong ground-motion values in the critical dam section. Armed with this real-time data, office professionals may begin analysis of the embankment and likelihood of structural damage. Not only may the Wappapello foundation and embankment be assessed following an event, but important liquefaction information will be provided to the geotechnical community. The liquefaction data of insitu pore-pressure increases due to simultaneously-read, strong-motion excitation will be very valuable.

REFERENCES

Dynamic Microprocessor Associates, Inc., 1990, Users Guide, Huntington, NY, 302 p.

Hempen, G.L., Ledbetter, R.H., and Finn, W.D.L., 1992, Proceedings of the Association of Engineering Geologists' Annual Meeting, Long Beach, CA (in press, 9 p.).

Kinemetrics, Inc., 1988, Installation Instructions for Downhole Accelerometer Equipped with Hole-lock Wedging System and Orientation Poles, Pasadena, CA, 9 p.

Kinemetrics, Inc., 1989, Operating Instructions for the Model SSA-1 Solid State Accelerograph, Pasadena, CA, 171 p.

Quarterdeck Office Systems, Inc., 1991, DESQ view Users Manual, Santa Monica, CA, 28 p.

USACE (U.S. Army Corps of Engineers), Engineer Office, Memphis, 1938, St. Francis River Project, The Wappapello Dam, Analysis of Design, Appendix II - Report on Soil Investigations, Memphis, TN, 151 p.

USAED-St. Louis (U.S. Army Engineer District-St. Louis), 1988, Earthquake Study for Wappapello Dam, St. Louis, MO, 99 p. plus appendices.

Wolff, T.F., Hempen, G.L., Dirnberger, M.M., and Moore, B.M., 1988, "Probabilistic Analysis of Earthquake-Induced Pool Release," Second International Conference on Case Histories in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, MO, Vol. I, pp. 787-793.